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Performance evaluations and applications of photovoltaic–thermal collectors and systems

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ABSTRACT

As a kind of renewable energy, solar energy is paid more and more attention all over the world. Solar energy utilization system can be classified into two categories: thermal systems which convert solar energy to thermal energy, and photovoltaic systems which convert solar energy to electrical energy. Normally, both types of the collectors are used separately. In solar thermal system, the solar thermal energy can be used for heating working fluid via a heat collector. The conventional electrical energy is used to circulate working liquid through the collector. The use of conventional electrical energy can be avoided if combination of both types of thermal collector and photovoltaic collector is hybrid in one unit named photovoltaic–thermal collector (PV/T). In order to fully develop the applications of the photovoltaic–thermal collectors and systems, more researches on performances and characteristics of the photovoltaic–thermal collectors and systems have been carried out.

This paper presents the performance evaluations and applications of the photovoltaic–thermal collectors and systems. The performances of the photovoltaic–thermal air collectors and photovoltaic–thermal water collectors are analyzed and discussed. The applications of the photovoltaic–thermal systems, such as building integrated photovoltaic–thermal systems, concentrating photovoltaic–thermal systems and photovoltaic–thermal heat pump systems are presented. Several factors affecting the performances and characteristics of the photovoltaic–thermal systems are also summarized.

Contents

1. Introduction

As a major renewable energy source with the most prominent characteristics of inexhaustibility and environmental friendliness, solar energy has great research values and broad application prospects. The solar energy technology has obtained significant development over recent years. Solar energy utilization system can be classified into two categories: thermal systems which convert solar energy to thermal energy, and photovoltaic (PV) systems which convert solar energy to electrical energy. The photothermal conversion technology plays an important role in

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the solar applications, and provides convenience for daily life, such as domestic hot water. The photothermal conversion technology is also used to satisfy the electric energy requirement through the energy transformation of light–heat–electricity. The photothermal conversion technology is to collect the solar energy by using large-scale parabolic mirror arrays, convert it to the thermal energy of working medium, and the steam drives the electric generator. The photovoltaic systems are mainly composed of a PV module, a controller and an inverter. PV modules are usually divided into two types: the thin-film PV module and the crystalline-silicon PV module. Both the monocrystalline silicon and the polycrystalline silicon cells belong to the latter. In additions, some other materials including noncrystalline silicon, gallium arsenide (GaAs) and copper indium diselenide (CIS) can be used to manufacture PV modules. The thin-film PV module is manufactured through the thin-film deposition on substrates. The common thin-film PV module is made by noncrystalline silicon, cadmium telluride (CdTe), etc. There are three primary types of the commercial PV modules: crystalline silicon, monocrystalline silicon and noncrystalline silicon. Under the same solar radiation conditions, the efficiency of the crystalline silicon cells is the highest; however, the monocrystalline silicon cell is more economically competitive because of its lower cost. However, more than 80% of the solar radiation falling on photovoltaic cells is not converted to electricity, but either reflected or converted to thermal energy. This leads to a drop of electricity conversion efficiency due to an increase in the photovoltaic cell's working temperature [1]. Tests show that every 1 °C rise in working temperature for crystalline silicon cells reduces the photovoltaic efficiency by 0.4% [2]. In practical applications, a large proportion of solar energy will be absorbed by solar cell in the form of heat energy, which is extremely difficult to be removed from solar cell by natural convection.

Normally, both types of the collectors are used separately. In solar thermal system, the solar thermal energy can be used for heating working fluid via a heat collector. Heat collectors are usually classified into the non-concentrating ones for utilizations of low-temperature heat energy and the concentrating ones for utilizations of high-temperature heat energy. The conventional electrical energy is used to circulate working liquid through the collector. The use of conventional electrical energy can be avoided if combination of both types of thermal collector and photovoltaic collector is hybrid in one unit named a photovoltaic–thermal (PV/T) collector [3]. The PV/T collector can produce thermal and electrical energy simultaneously. A number of theoretical and experimental studies have been made on the hybrid photovoltaic–thermal collectors with air or water as the working fluid.

The photovoltaic–thermal systems with air or water collectors not only produce electricity, but also provide heat for space heating and other applications. The cell efficiency can be improved by maintaining its suitable operating temperature. The electricity production can be also increased as a result of the PV modules cooling by ventilation air heating and hot water production with PV/T modules. Because the photovoltaic–thermal collectors and systems are still studied and developed in experiment phase, their applications are not implemented extensively. In order to understand systemically the characteristics of all photovoltaic–thermal collectors and systems, the performance evaluations of all kinds of the photovoltaic–thermal collectors and systems, such as the photovoltaic–thermal air collectors and photovoltaic–thermal water collectors, the building integrated photovoltaic–thermal systems, concentrating photovoltaic–thermal systems and photovoltaic–thermal heat pump systems ought to be summarized in this paper.

The photovoltaic–thermal collectors are the significant components of the photovoltaic–thermal systems. Therefore, the performance evaluations of the photovoltaic–thermal collectors are firstly presented, then the performances of the building integrated photovoltaic–thermal systems, concentrating photovoltaic–thermal systems and photovoltaic–thermal heat pump systems are further analyzed and discussed.

2. Photovoltaic–thermal collectors

The hybrid photovoltaic–thermal collectors can be classified as photovoltaic–thermal air collectors and photovoltaic–thermal water collectors according to the type of working fluid used. Some theoretical and experimental researches on these two types of photovoltaic–thermal collectors have been carried out in recent years.

2.1. Photovoltaic–thermal air collectors

The performances of the photovoltaic–thermal air collectors have been paid much attention by researchers. The performances of single-pass and double-pass combined photovoltaic thermal collectors were analyzed with steady-state models. The results showed that the double-pass photovoltaic thermal collector had superior performance over the single-pass photovoltaic thermal collector. At a length of 1 m, a mass flow rate of 200–300 kg/h, and a packing factor of 0.5, the thermal, photovoltaic, and combined efficiencies were 24–28%, 6–7%, and 30–35% for the single-pass photovoltaic thermal collector. The thermal, photovoltaic, and combined efficiencies were 32–34%, 8–9%, and 40–45% for the double-pass photovoltaic thermal collector [4].

In order to improve heat extraction from the PV module as a PV/T air collector by natural flow, the thin metal sheet was suspended at the middle or fins were attached to the back wall of the air-channel. The REF type consists of a simple air channel attached behind the PV module while the TMS has a thin (flat) metal sheet suspended at the middle of the air channel and the FIN system has fins of rectangular profiles attached on the opposite wall to the PV rear surface parallel to flow direction. The modified systems presented better performance than the usual type. For the glazed modified systems, the TMS had about 4 °C and FIN had about 10 °C lower temperatures than that of the REF system at channel depth of 15 cm and represented respectively about 4% and 10% improvement in output power [5].

A theoretical model of a direct-coupled PV/T air collector with a thin aluminum sheet suspended at the middle of air channel was developed. There was good agreement between experimental and theoretical results for air mass flow rate, outlet air temperature and PV panel temperature. It was concluded that thermal efficiency increased with increasing the air mass flow rate due to increased heat transfer coefficient and there was an optimum number of fans for achieving maximum electrical efficiency. The results also indicated that setting glass cover on photovoltaic panels leads to an increase in thermal efficiency and decrease in electrical efficiency of the system [6].

The experimental validation for glazed hybrid PV/T module air collector had been carried out on clear days during the month July 2010–June 2011. Fig. 1 shows the schematic diagram of glazed hybrid PV/T module air collectors connected in series. The PV modules were mounted on a rectangular polyvinylchloride (PVC) sheet air duct of area 0.54 m × 1.12 m and depth 0.02 m. It was observed that average power generated by the PV module was 141.4 W and consumed by direct current (DC) fan was 21.3 W, and the net saving of DC power generated was 120.1 W during the sunshine hours for a typical day in summer month (April 10, 2011). It was also noted that the annual electrical energy generated by a hybrid PV/T air collector and consumed by a DC fan were 287.6 kW h and 44.2 kW h, and the annual net electrical energy saving by the glazed hybrid PV/T air collector was 243.4 kW h for the year 2010–2011 analysis. The annual overall thermal energy

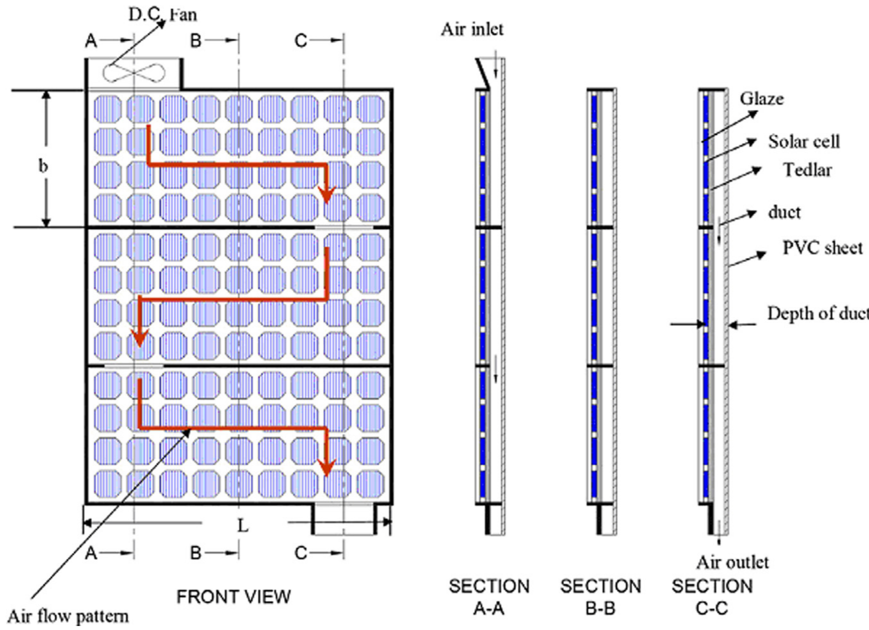

Fig. 1. A schematic diagram of glazed hybrid PVT module air collectors connected in series [7].

and exergy gain were 1252.0 kW h and 289.5 kW h respectively [7].

The performance evaluation of a photovoltaic/thermal (PV/T) solar air heater with a double pass configuration and vertical fins in the lower channel was performed. The effects of the presence of fins in the lower air channel, the depth of ducts of the air channels, flow rate, in let air temperature and packing factor were evaluated on the thermal and electrical efficiencies. The extended fin area reduced the cell temperature from 82 °C to 66 °C. It was noted that the addition of fins increased the thermal and electrical efficiencies to 15.5% and 10.5%, respectively. The maximum thermal output obtained from the PV/T collector corresponded to an air mass flow rate of about 0.12 kg/s. The thermal and electrical efficiencies declined to about 30% and 9.5% at an air mass flow rate of 0.15 kg/s, which was attributed to high cell temperature. The increase in the electrical efficiency was also observed about 20% as the air mass flow rate changed from 0.03 kg/s to 0.15 kg/s. The total equivalent thermal electrical efficiency of the PV/T collector increased about 17% as the packing factor changed (0.38–0.98) [8].

The performance analysis of different types of photovoltaic thermal (PV/T) air collector with unglazed hybrid PV/T tiles, glazed hybrid PV/T tiles and conventional hybrid PV/T air collectors was investigated. It was found that the overall annual thermal energy and exergy gain of an unglazed hybrid PV/T tiles air collector was higher by 27% and 29.3% as compared to the glazed hybrid PV/T tiles air collector, and by 61% and 59.8% as compared to the conventional hybrid PV/T air collector. It was also observed that the overall annual exergy efficiency of unglazed and glazed hybrid PV/T tiles air collectors was higher by 9.6% and 53.8% respectively as compared to the conventional hybrid PV/T air collector [9].

The experiments of the four different configurations of PV modules with glass to glass PV module with duct, glass to glass PV module without duct, glass to tedlar PV module with duct and glass to tedlar PV module without duct were carried out under composite climate of New Delhi. It was observed that the glass to glass PV modules with duct had higher electrical efficiency as well as the higher outlet air temperature amongst the all four cases. The annual average efficiency of glass to glass type PV module with and without duct was 10.41% and 9.75%, respectively [10].

The performances of the photovoltaic (PV) module integrated with an air duct for composite climate of India were investigated. The experimental validation of thermal model of hybrid photovoltaic/thermal (PV/T) system was implemented. The results showed that the maximum back surface temperature of module in the month of January for a typical day was 49.4 °C under natural mode, and the back surface temperature of module was lower by 1–8 °C than the top surface temperature of module in all cases. It was found that there was a drop in back surface temperature of module with one fan by 5 °C in comparison with the natural mode due to withdrawal of heat from back surface of the module. It was also noted that an overall efficiency of panel increased initially and then decreased after attaining the flow rate of about 2 m/s. The results indicated that an overall efficiency increased with an increase of duct depth, and the optimum value of duct depth was between 0.03 and 0.06 m [11].

The exergetic performances of a solar PV/T air collector were evaluated. A detailed energy and exergy analysis was carried out to calculate the thermal and electrical parameters, exergy components and exergy efficiency of a typical PV/T air collector. It was observed that the thermal efficiency, electrical efficiency, overall energy efficiency and exergy efficiency of PV/T air collector were about 17.18%, 10.01%, 45% and 10.75% respectively [12].

The performance evaluations of a hybrid photovoltaic thermal (semitransparent PV/T) double pass facade for space heating were carried out. It was found that the annual thermal and electrical energies were 480.81 kW h and 469.87 kW h respectively. The yearly overall thermal energy generated by the system was calculated as 1729.84 kW h. It was also observed that the room air temperature was around 5–6 °C higher than the ambient air temperature for a typical winter day [13].

The performances of a hybrid PV/T parallel plate air collector were investigated for four climatic conditions of India. Fig. 2 illustrates the schematic diagram of a PV/T air collector. Two PV modules with an effective area of 0.61 m^2 each were connected in series. The module was mounted on a wooden structure with the air duct below the module known as tedlar. The tedlar was an insulating and non-corrosive material used beneath the solar cell for better support to the PV module. The results indicated that an instantaneous energy and exergy efficiency of the PV/T air heater

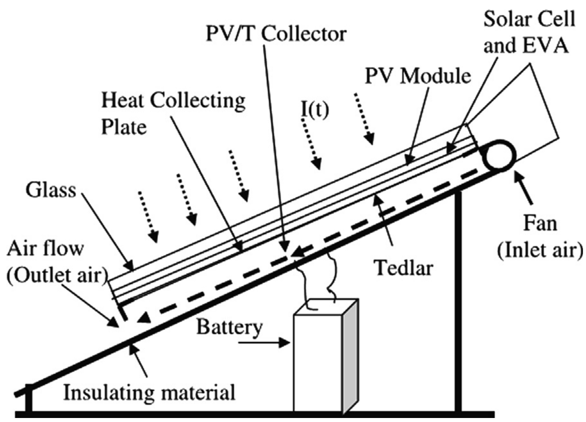

Fig. 2. A schematic diagram of a PV/T air collector [14].

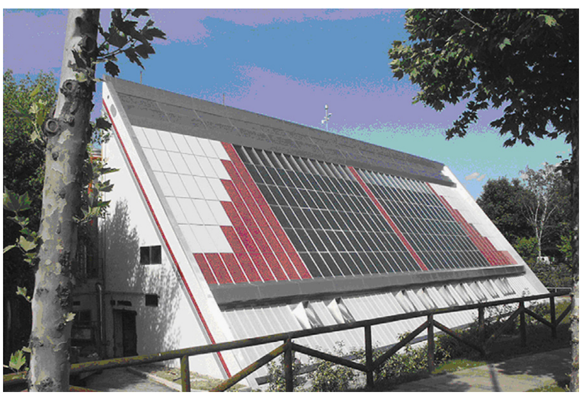

Fig. 3. The hybrid photovoltaic–thermal facade of the Fiat Research Centre (CRF) [15].

varied between 55–65 and 12–15%, respectively. It was also found that the monthly total energy varies between 35 and 65 kW h and corresponding exergy varied between 8 and 15 kW h [14].

The successful commercial application of the TIS (integrated solar roof) system for building integration of hybrid PVT air collectors was presented as a case study. Fig. 3 shows the hybrid photovoltaic–thermal facade of the Fiat Research Centre (CRF) at Orbassano, Italy, which represented the first commercial realization of the TIS system. The photovoltaic plant had a total power of 20 kWp and the hot air produced by the system was used for air-conditioning of the office building in winter (preheating) as well as in summer (desiccant cooling). The experimental results on the thermal and electrical efficiencies of hybrid facade for the summer (18 May) and winter (15 January) days showed that the thermal efficiency varied in average from 20% to 40% during the day and the average electrical efficiency obtained was around 9–10% during the day [15].

The performances of two type of photovoltaic (PV) module with glass-to-tedlar and glass-to-glass were evaluated. The results showed that the back surface temperature for glass-to-tedlar varied from a minimum value of 43.6 °C at 8 am to a maximum value of 68 °C at 12 pm whereas for a glass-to-glass PV/T air collector it varied from a minimum value of 44 °C at 8 am and 5 pm and a maximum value of 71 °C at 12 pm. The solar cell temperature was almost same for both cases and ranged between a minimum value of 45 °C at 8 am and 5 pm to a maximum value of 70 °C at 12 pm. The outlet air temperature changed between a minimum value of 33 °C at 8 am and a maximum value of 46 °C at 1 pm and it was slightly higher in the glass-to-glass air collector. It was also observed that the electrical efficiency in both cases

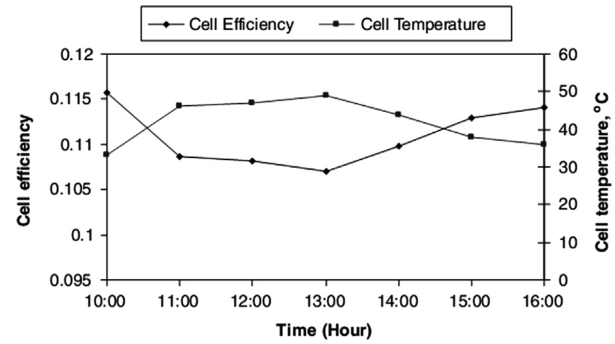

Fig. 4. The hourly variation of cell efficiency and cell temperature in the month of February 2007 [18].

changed between 9.5 and 11% throughout the day and the thermal equivalent of electrical efficiency for both cases ranged between 26.4 and 30.5%. The thermal efficiency changed between 15.7 and 18.3% for the glass-to-glass PV/T air collector and 13.4 and 16.5% for the glass-to-tedlar case. The overall thermal efficiency was 43.4–47.4% for the glass-to-glass and 41.6–45.4% for the glass-to-tedlar case [16].

The energy and exergy analysis of a hybrid micro-channel photovoltaic thermal (MCPVT) module based on proposed micro-channel solar cell thermal (MCSCT) was carried out by considering four weather conditions for different climatic conditions of India. The results indicated that the overall annual thermal gain of the proposed MCPVT module was increased by 70.62%, 73.88%, 74.05% and 72.59% over single channel photovoltaic thermal (SCPVT) module for Srinagar, Bangalore, Jodhpur and New Delhi Indian climatic conditions respectively, the overall annual exergy gain of the proposed MCPVT module was increased by 60.19%, 63.47%, 62.41% and 60.47% over SCPVT module for Srinagar, Bangalore, Jodhpur and New Delhi Indian climatic conditions respectively, and the overall annual exergy efficiency of the proposed MCPVT module was increased by 57.61%, 63.19%, 61.08% and 58.43% over SCPVT module for Srinagar, Bangalore, Jodhpur and New Delhi Indian climatic conditions respectively [17].

2.2. Photovoltaic–thermal water collectors

The performances of a photovoltaic (glass–glass) thermal (PV/T) solar water heater were carried out during February–April, 2007. It was observed that the storage tank water temperature in the month of February 2007 varied from a minimum value of 29 °C at 10:00 to a maximum value of 59 °C at 14:00, from a minimum value of 32 °C at 10:00 to a maximum value of 80 °C at 15:00 in the month of March 2007 and from a minimum value of 34 °C at 9:00 to a maximum value of 62 °C at 16:00 in the month of April 2007. Fig. 4 presents the hourly variation of cell temperature and cell efficiency. It was known from the figure that the increase in cell temperature decreases the cell efficiency. As the cell temperature at 10:00 was about 34 °C, the cell efficiency was about 11.6%. As the cell temperature at 13:00 was about 50 °C, the cell efficiency was about 10.7% [18].

The performances of partially covered flat plate water collectors connected in series were evaluated. The results showed that the tank water temperature increased from 69.6 °C to 95.4 °C as the number of collectors increased from 2 to 10 at constant mass flow rate (m=0.01 kg/s) and increased from 71.5 °C to 97.7 °C as the mass flow rate increased from 0.005 to 0.08 kg/s for a fixed number of collectors (N=4). Daily overall thermal energy and exergy yields obtained were 43.3 and 4.26 kW h at constant flow rate and collectors (N=6 and m=0.04 kg/s). The monthly yield in thermal energy, exergy and electrical energy was evaluated by

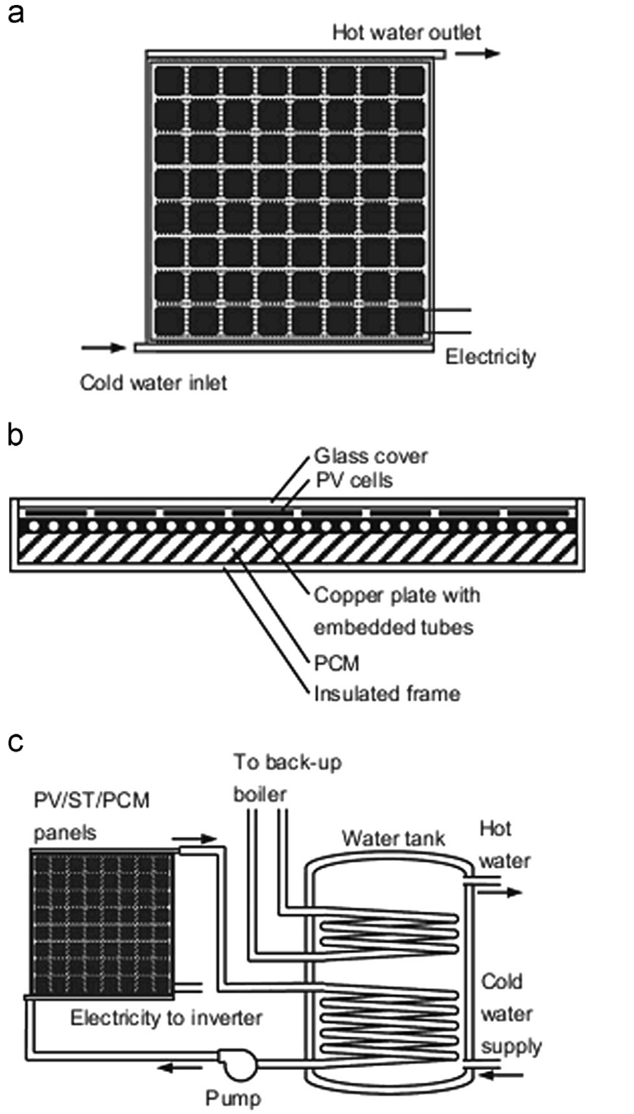

Fig. 5. A schematic diagram of a generic combined photovoltaic (PV) solar thermal (ST) system that incorporated phase change material (PCM). (a) A plan view, (b) a cross-sectional view and (c) a typical installation for an active closed-loop system appropriate for a single dwelling [20].

considering the six collectors connected in series and at a constant mass flow rate of 0.04 kg/s. The total annual yield for thermal energy, electrical energy and exergy was 12,824.2, 211 and 1273.7 kW h, respectively [19].

The performances of a generic combined photovoltaic (PV) solar thermal (ST) system that incorporated phase change material (PCM) were carried out. In order to evaluate general PV and ST performance, a generic system with a panel surface area of 1 m × 1 m was considered. Fig. 5 shows the schematic diagram of a generic combined photovoltaic (PV) solar thermal (ST) system that incorporated phase change material (PCM). An active (pumped) circulation provided freedom to locate the tank below the level of the panels and also enabled accurate control of the water flow rate. The results indicated that the PV output increased by 6.5% demonstrating the significant benefit of using PCM as the PCM thickness increased from 0 m to 0.03 m, and increasing the PCM conductance by a factor of 10 increased the PV output by 3%. The PV output was increased by typically 9% with an average water temperature rise of 20 °C by including an appropriate PCM in an optimized system [20].

The thermal and electrical performances of a single glazed flat plate photovoltaic–thermal solar collector based on water

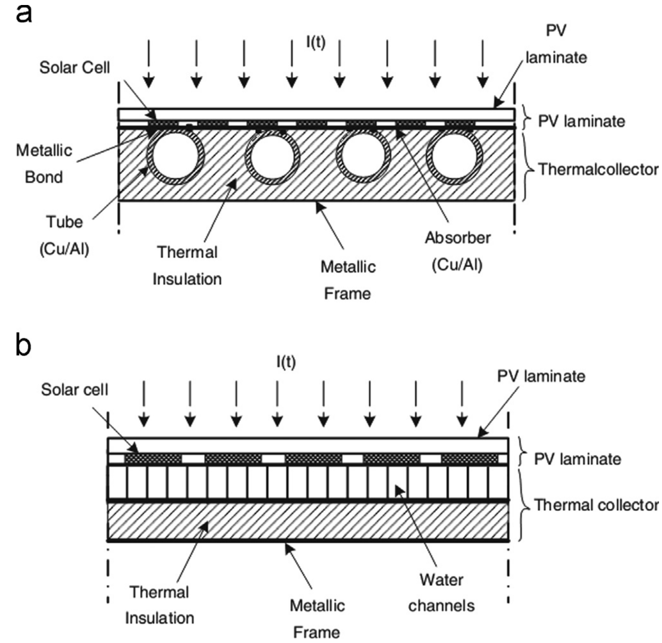

Fig. 6. (a) Cross-sectional view of Type A PVT module, (b) cross-sectional view of Type B PVT module [24].

circulation were investigated. It was noted that the thermal efficiency at zero reduced temperature was 79% under PV operation with a corresponding electrical efficiency of 8.8%, leading to a high overall efficiency of almost 88%. These experimental results indicated a significant improvement of both thermal and electrical performances in comparison to the previous work on PV–T collectors [21].

The thermal energy, electrical energy and exergy gain of hybrid photovoltaic thermal (PVT) water collectors under constant collection temperature mode for two different configurations namely case A (collector partially covered by the PV module) and case B (collector fully covered by the PV module) were evaluated. It was observed that case A was more favorable for hot water production, while case B was suitable for electricity production. The results indicated that the annual thermal energy gain was 4167.3 kW h and 1023.7 kW h and the net annual electrical energy gain was 320.65 kW h and 1377.63 kW h for cases A and B respectively. The annual overall thermal energy gain was decreased by 9.48% and the annual overall exergy gain was increased by 39.16% from case A to case B [22].

The performances of facade-integrated hybrid photovoltaic–thermal collector systems with EPV (film cell) and BPV (single silicon cell) panels for use in residential buildings of Hong Kong were carried out. The results showed that the annual electric efficiencies of the hybrid EPV/T and BPV/T systems were 4.3% and 10.3% for a west-facing panel, and the annual overall thermal efficiencies were 58.9% and 70.3%, respectively. The annual efficiencies of the water heating systems were 47.6% (for EPV) and 43.2% (for BPV), respectively; the corresponding number of days in a year when the water temperature in the storage tank reached 45 °C and above was 195 and 217. The reduction of space heat gain through the two kinds of hybrid PV/T collector wall could reach 53.0% and 59.2% respectively as compared with a normal concrete wall [23].

The thermal and PV efficiencies of two different types (Type A with monocrystalline Si solar cells and integrated with a tube-and-sheet type thermal collector and Type B with multi-crystalline Si solar cells and integrated with a parallel-plate type thermal collector) of commercially available PV/T modules were evaluated under the tropical climatic conditions of Singapore. Fig. 6 shows the cross-sectional views of the flow channels for both PV/T types.

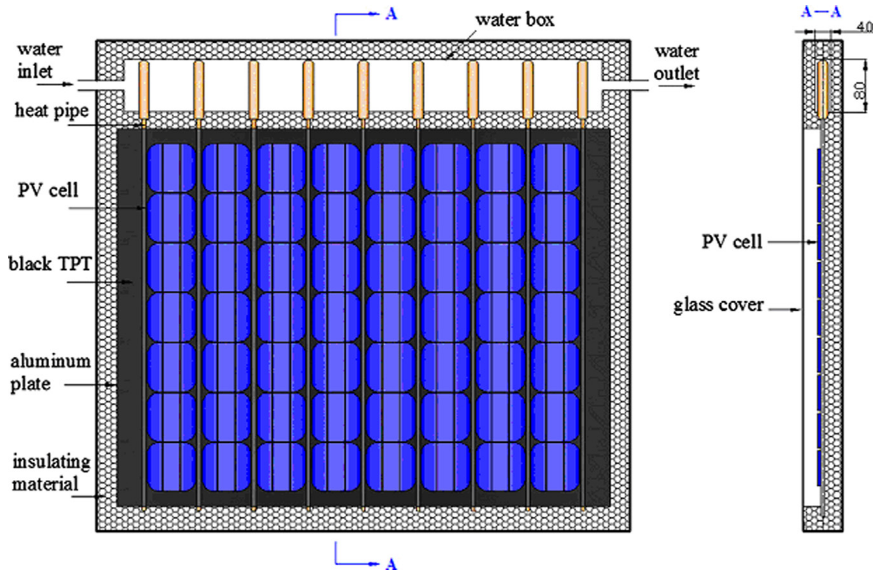

Fig. 7. A schematic diagram of a HP-PV/T solar collector [25].

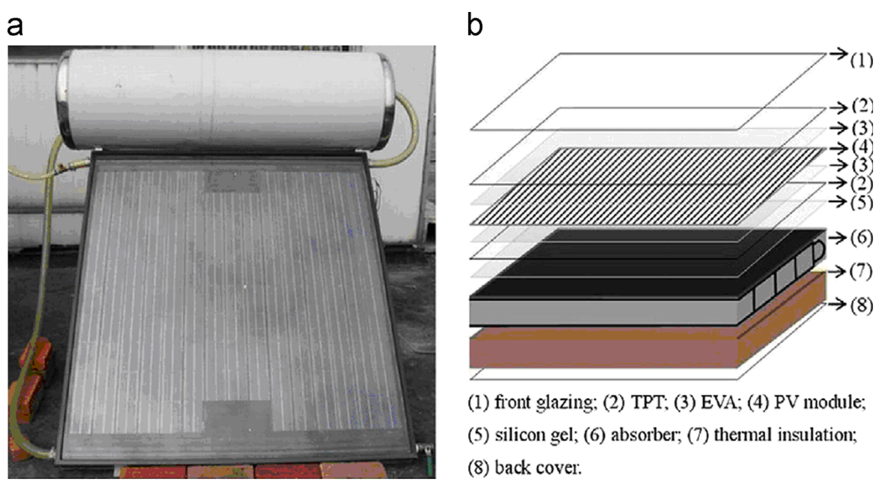

Fig. 8. The configuration of the hybrid PV/T water collector: (a) front view and (b) the constituent layers [26].

The effective module areas of Type A and Type B were 1.267 m^2 and 1.47 m^2, respectively. The results indicated that the average thermal efficiency and P V efficiency for Type A PV/T module were 40.7% and 11.8%, respectively, and for Type B were 39.4% and 11.5%, respectively. The electrical efficiency of the PV modules was also compared with and without the thermal collector, and it was noted that the average PV efficiency of the PV/T modules was about 0.4% higher than the normal PV module. It was also found out that Type B was suitable for low pressure (1–3 bars) applications while Type A could be used under high pressure (up to 10 bars) [24].

The electrical and thermal performances of the heat-pipe photovoltaic/thermal (HP-PV/T) systems used in three typical climate areas of China, namely Hong Kong, Lhasa, and Beijing, were studied. Fig. 7 illustrates the structure of the HP-PV/T solar collector. A piece of aluminum plate was chosen as the base panel. The evaporator section of the heat pipes was connected to the back of the aluminum plate, and the condenser section was inserted into a water box. It was found that the annual thermal energy was 1665.05–1872.22 MJ/m^2, 2939.67–3328.25 MJ/m^2, and 2111.07–2352.95 MJ/m^2 when the system with auxiliary heating equipment was used in Hong Kong, Lhasa, and Beijing, respectively. The annual electrical energy produced was 261.32–264.98 MJ/m^2, 462.14–466.1 MJ/m^2, and 322.84–328.15 MJ/m^2, respectively. It was also concluded that the solar thermal contribution mainly depended on the available solar radiation and the hot-water load per unit collecting area (M_w/A_c). When M_w/A_c was 64.5 kg/m^2, the annual solar thermal contribution of the HP-PV/T system in Hong Kong, Lhasa, and Beijing was 68.5%, 80.5%, and 64.7%, respectively [25].

The PV/T water heating system was designed with natural circulation and experiments were conducted with different water masses and different initial water temperatures in an outdoor environment. Fig. 8 shows the configuration of the hybrid PV/T water collector. The prototype was constructed from 15 battens, with a total heat-collecting area of 1.76 m^2. The whole PV/T assembly was housed in an Al-alloy frame, giving the overall dimension 1.33 $\times$ 1.5 m. The results indicated that as the hot-water load per unit heat-collecting area exceeded 80 kg/m^2, the daily electrical efficiency was about 10.15%, the characteristic daily thermal efficiency exceeded 45%, the characteristic daily total efficiency was above 52% and the characteristic daily primary-energy saving was up to 65%, for this system with a PV cell covering factor of 0.63 and a front-glazing transmissivity of 0.83 [26].

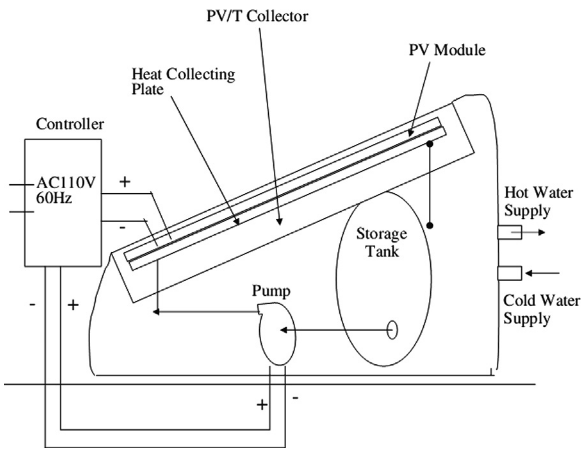

Fig. 9. A schematic diagram of an integrated PV/T system [27].

The performances of an integrated photovoltaic and thermal solar (IPVTS) water/air heating system were evaluated. Fig. 9 illustrates a schematic diagram of an integrated PV/T system. The storage tank of capacity 45 kg was connected with the PV module with an effective area of 0.64 m^2 (0.54 m $\times$ 1.2 m) through insulated pipes. Comparisons of the IPVTS system with water and air heater were carried out. It was noted that the characteristic daily efficiency of the IPVTS system with water was higher than with air for all configurations except GWT. It was also observed that an overall thermal efficiency of the IPVTS system for summer and winter conditions was about 65% and 77%, respectively [27].

An experimental study of a centralized photovoltaic and hot water collector wall system was carried out. Fig. 10 shows the building-integrated photovoltaic/thermal (BiPV/T) system with hot water generation. The overall dimensions of the environmental chamber were 7.3 m (L) $\times$ 4.0 m (W) $\times$ 3.7 m (H). Within the outer chamber there were two identical inner chambers(test cells), each

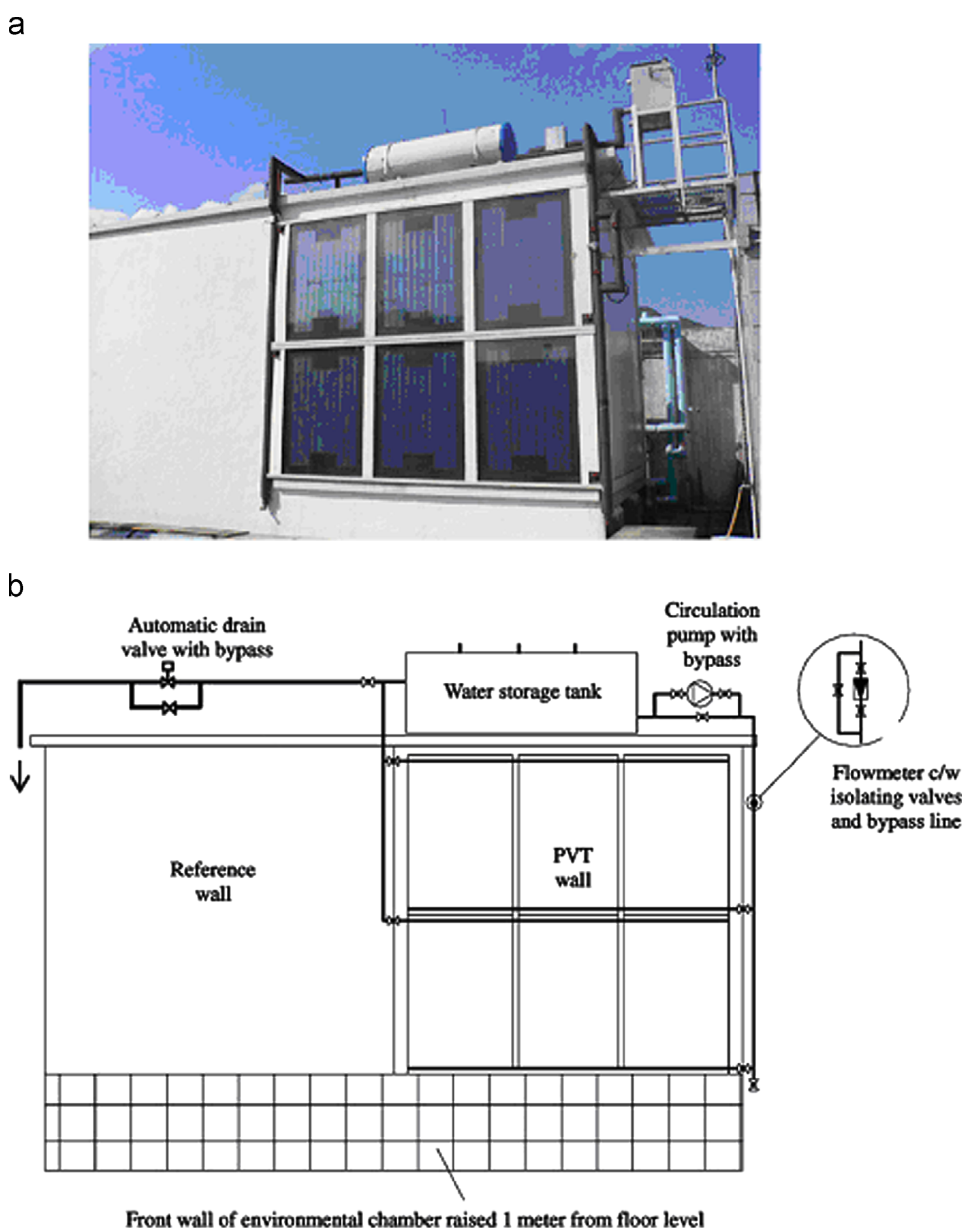

Fig. 10. The building-integrated photovoltaic/thermal (BiPVT) system with hot water generation: (a) BiPVT system and the environmental chamber, (b) schematic diagram of water-heating circuit [28].

of size 3 m $(L) \times 3$ m $(W) \times 2.8$ m (H). It was found that natural water circulation was more preferable than forced circulation in this hybrid solar collector system. The results indicated that the thermal efficiency was 38.9% at zero reduced temperature, and the corresponding electricity conversion efficiency was 8.56%, during the late summer of Hong Kong. It was found that the interior surface temperature of the PV/T wall varied with much smaller amplitude and with a time lag of 2–3 h as compared with the bare wall situation, and the space cooling load was also reduced by 50% in peak summer [28].

A comparative test of the photovoltaic and thermal solar system with a monocrystalline silicon PV/T solar collector, a traditional solar collector and a monocrystalline silicon photovoltaic plate was performed. Fig. 11 shows a photograph of the photovoltaic and thermal experimental system. The PV/T solar collector carried a thermally insulated 100 L water storage tank. The PV/T collector and the traditional solar collector were the same collecting areas and the solar cell covered area of the PV/T collector was the same as the area of the photovoltaic plate. It was found that the final water temperature in the storage of the PV/T system had reached about 55 °C, while the final water temperature in the storage of the traditional solar collecting system could reach about 63 °C in the same conditions. The experimental results indicated that the daily thermal efficiency of the PV/T system was about 40%, which was about 75% of that for a traditional solar thermosiphon system, and the daily average electrical efficiency was about 10%, which was a little lower than the photovoltaic module. But primary-energy saving efficiency of the PV/T system was much higher than that of the individual PV plate and the traditional solar collector [29].

The performances of the photovoltaic (PV)/thermal solar hybrid systems with the employment of a bifacial PV module were evaluated. The results showed that the total maximum electric power of the PV module was 102 W and the total electric energy produced per day was 617 Wh for the mid-summer time. For mid-winter, the power was 80 W and the energy was 380 Wh. It was found that in all cases these values were larger than the electric energy produced by standard one-facial c-Si PV modules with the same area. It was also noted that the total thermal energy collected by the water (per day) and stored in a thermal tank was 2130 Wh at mid-summer time and 1675 Wh at mid-winter. The estimated thermal efficiency of the PVT hybrid system was about 50% [30].

3. Building integrated photovoltaic–thermal systems

The electrical and thermal performances of the building-integrated photovoltaic–thermal (BIPV/T) system combined PV panels with solar thermal collectors were evaluated. Fig. 12 shows the building facade design with BIPV and BIPV/T systems for the simulation model. The BIPV or BIPV/T system was placed on the south facade of the building model with 128 PV modules of a total

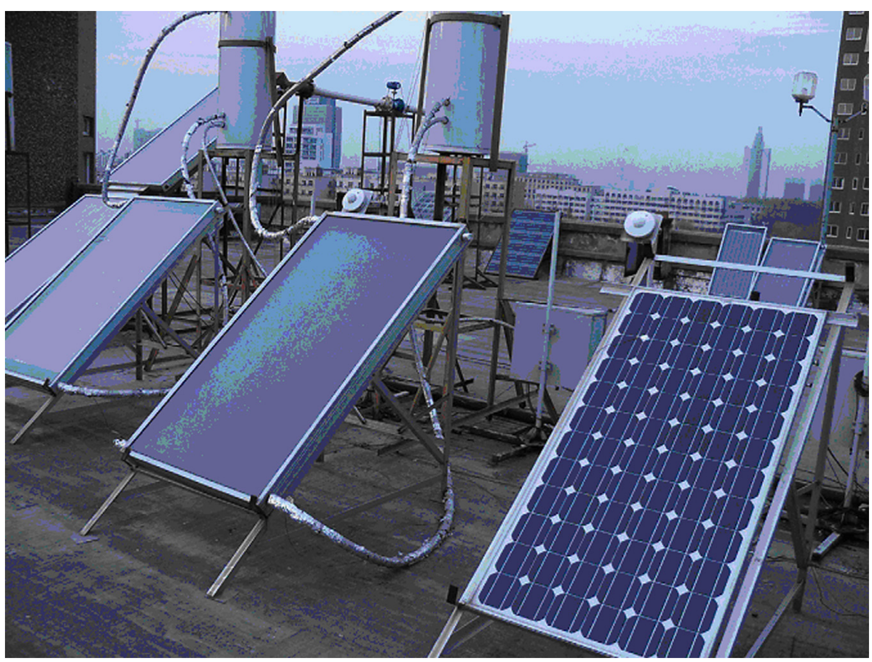

Fig. 11. A photograph of the photovoltaic and the thermal experimental system [29].

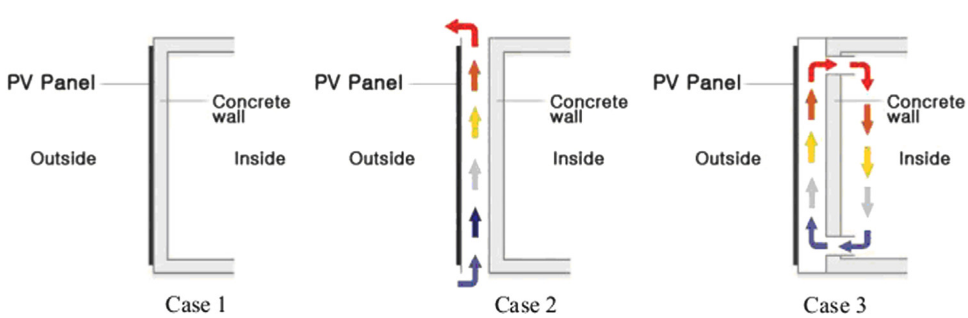

Fig. 12. The building facade design with BIPV and BIPVT systems for a simulation model [31].

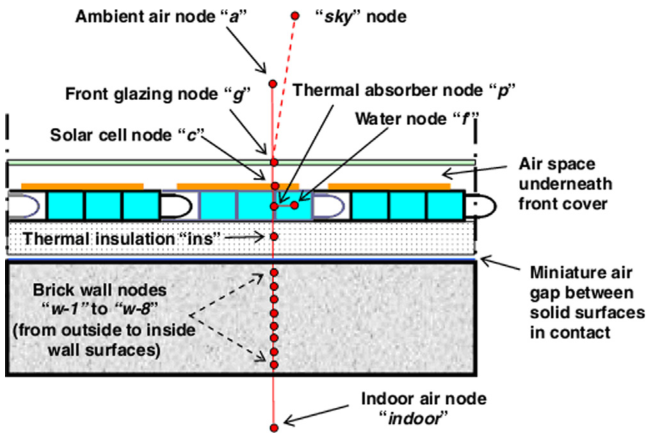

Fig. 13. A cross-sectional view cutting horizontally across one part of the BiPVW wall [33].

rated power of 16 kWp over an area of 129 m^2. The air gap distance between BIPV modules and building wall surface was 10 cm and the air flow rate was 9310 kg/h. The results indicated that the electricity generation of cases 2 and 3 was higher annually 6% and 3% respectively due to PV module cooling of the BIPV/T envelope than that of the building with the BIPV envelope of the case 1. It was found that the thermal efficiencies of cases 2 and 3 were average 30% and 14% respectively in the winter season that solar radiation was higher than that of the summer, and the heat gains of cases 2 and 3 were average 3900 kW h and 1840 kW h respectively [31].

The performances of a building integrated photovoltaic/thermal (BIPV/T) collector were investigated to determine the effect of flow distribution on the photovoltaic yield of the BIPV/T collector. The results indicated that flow distribution within the collector had a significant influence on the photovoltaic performance of the hybrid PV/T collector. It was found that the photovoltaic performance was improved by over 9% in comparison to a traditional photovoltaic (PV) collector operating under the same conditions for the uniform flow distribution, and performance was only improved by approximately 2% for poor flow. The calculated results indicated that the net electric yield from the PV/T array was 550.4 W in the best case scenario, and the yield of a traditional photovoltaic collector operating under the same test conditions was 502.9 W due to its high operating temperature [32].

The performances of a building-integrated photovoltaic/water-heating (BiPV/W) system were analyzed. Fig. 13 illustrates a cross-sectional view cutting horizontally across one part of the BiPV/W wall. The PV/W collector was mounted on the brick wall. The PV/W collector was divided into interconnecting vertical segments along the water flow channels. The calculated results showed that the system thermal performance under natural water circulation was better than the pump-circulation mode. It was found that the water heat gains for the natural and forced circulation modes were respectively 1011 MJ/m^2 and 965 MJ/m^2 (5% difference) based on a unit collector area, and the electrical gains after the deduction of pump consumption were respectively 239 MJ/m^2 and 167 MJ/m^2 (43% difference) based on the unit PV cell area. It was also observed that the year-average thermal and cell conversion efficiencies were respectively 37.5% and 9.39%, and the two modes of operation reduced the thermal transmission through the PVW wall by about 72% and 71% respectively as compared with the normal building facade [33].

The performances of a building integrated photovoltaic thermal (BIPV/T) system were evaluated for four different parallel and series combinations under the cold climatic conditions of India. Fig. 14a shows a photograph of the BIPV/T systems fitted as a rooftop. Fig. 14b illustrates an orthographic view of the experimental laboratory with BIPV/T systems as the rooftop at Srinagar. The roof was fitted with a total of 48 BIPV/T systems spread over six rows each having eight BIPV/T systems covering an area 65 m^2 and could produce a total of 7.2 kWp. An air blower consuming 0.12 kWp was used to circulate the air through the duct at a constant mass flow rate of 1.2 kg/s. It was found that the series combination was more suitable for the buildings fitted with BIPV/T systems as the rooftop for a constant mass flow rate of air. The results showed that the BIPV/T system, fitted on the rooftop in an effective area of 65 m^2, produced an annual electrical and thermal exergies of 16,209 kW h and 1531 kW h with an average overall thermal efficiency of 53.7%. It was observed that the net exergy output was up to 975 kW h higher than any other combination of the BIPV/T systems and up to 2713 kW h higher than a BIPV system. It was also concluded that the parallel combination provided the overall thermal efficiency of 50% which was higher than the any other combinations for a constant velocity of air. The energy and exergy performances of a building integrated semi-transparent photovoltaic thermal (BISPV/T) system integrated to the roof of a room with dimensions of 3 m × 1.81 m × 4 m and PV roof area of 5.44 m^2 were evaluated. The BISPV/T system could produce electrical and thermal energy. The thermal energy was used for space heating by natural circulation of air, which could reduce the PV module's temperature and increase the electrical efficiency. It was found that maximum annual electrical energy was 810 kW h for heterojunction comprised of a thin amorphous silicon (a-Si) PV cell on top of a crystalline silicon (c-Si) cell (known as HIT) and the maximum annual thermal energy was 464 kW h for a-Si. It is also noted that the HIT PV module was suitable for producing electrical power whereas a-Si was suitable for space heating. The results showed that an annual overall maximum thermal energy was 2497 kW h and exergy was 834 kW h for the HIT PV module. It was observed that the cell temperature was minimum (42 °C) with maximum efficiency of 16.0% in case of HIT, and the cell temperature was maximum (49 °C) with minimum efficiency of 6.0% in case of a-Si. The results indicated that the maximum and minimum values of electrical power for HIT and a-Si were 779 W and 287 W, and the maximum and minimum thermal energies for a-Si and HIT were 408 W and 321 W respectively [35].

A novel building integrated photovoltaic–thermal (BIPV/T) collector was investigated to determine the effect of active heat recovery on cell efficiency. The BIPV/T collector was originally designed and constructed for the 2007 US Solar Decathlon by the University of Colorado Solar Decathlon Team. The collector consisted of 41 photovoltaic panels suspended above an array of tube-fin absorbers. The absorbers were plumbed as two parallel arrays to copper pipes connected to an insulated thermal storage tank. Water from the tank was circulated to the absorbers beneath the photovoltaic panels by a pump, and was heated by convection and radiation from the back surface of the photovoltaic panels. The results showed that the temperatures during testing reached 57.4 °C at an ambient temperature of 35.3 °C, which was hot enough for domestic hot water use. It was observed that thermal efficiency at zero inlet and ambient temperature differential was 19.0%, and combined thermal and electrical efficiency was 32.9%. It was also found that the 10 °C inlet water temperature at 1000 W/m^2 resulted in cell temperatures 13.2 °C lower than the natural convection case when averaged over the collector area, and a standard silicon cell with a temperature coefficient of 0.4%/°C at an average of 13.2 °C reduction in temperature resulted in a 5.3% increase in conversion efficiency [36].

The performances of the building integrated photovoltaic thermal (BIPV/T) system fitted as the rooftop of a building to

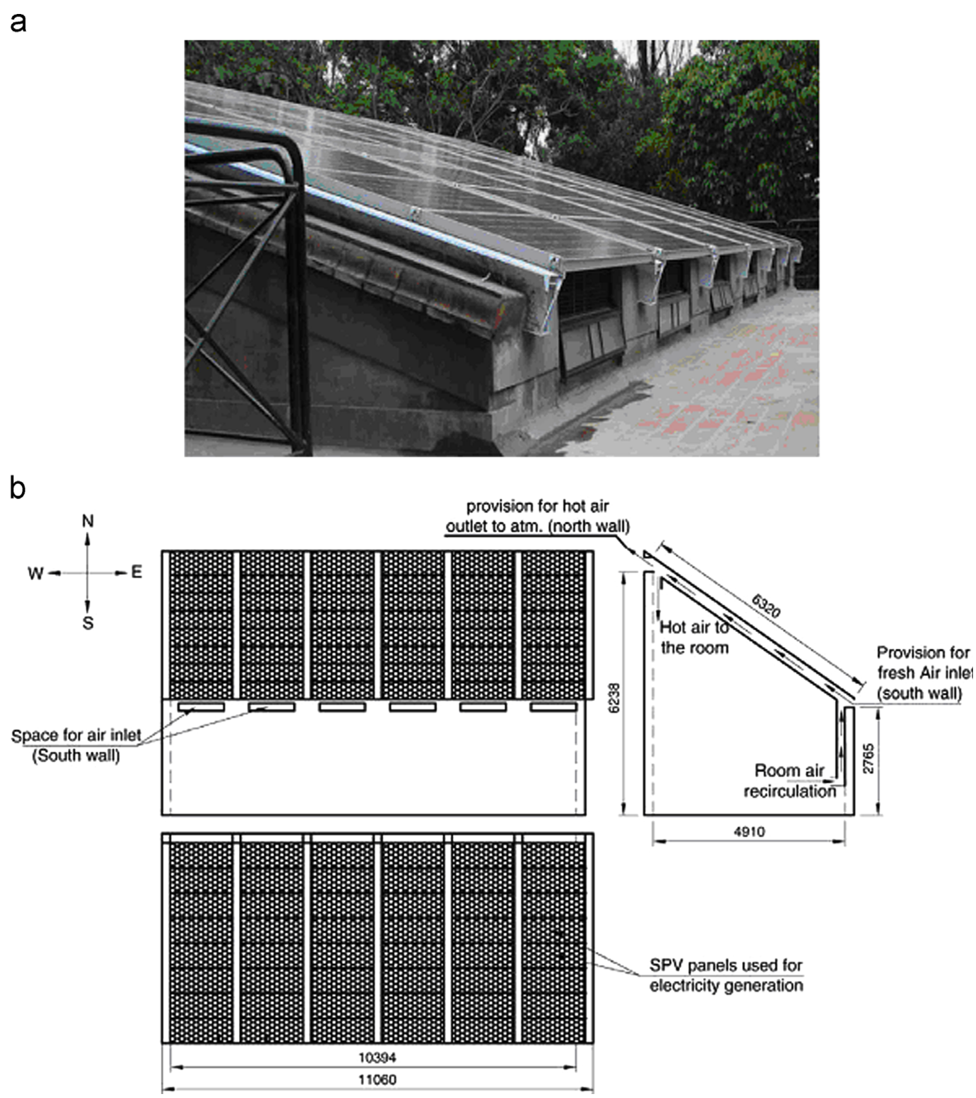

Fig. 14. (a) A photograph of the BIPVT systems fitted as rooftop. (b) Orthographic view of the experimental laboratory with BIPVT systems as the rooftop at Srinagar [34].

generate electrical energy higher than that generated by a similar building integrated photovoltaic (BIPV) system were evaluated. The results showed that although the monocrystalline BIPV/T system was more suitable for residential consumers from the viewpoint of the energy and exergy efficiencies, the amorphous silicon BIPV/T system was more economical. It was observed that the annual electrical output from the monocrystalline silicon (c-Si) BIPV/T was maximum (15,131 kW h) while that of the amorphous silicon (a-Si) BIPV/T was minimum (6066 kW h), and the annual thermal output of the monocrystalline silicon (c-Si) BIPV/T was minimum (16,764 kW h) while that of the amorphous silicon (a-Si) BIPV/T was maximum (20,615 kW h). The results indicated that the annual exergy output was maximum (16,225 kW h) in case of c-Si BIPV/T system and minimum (7790 kW h) in case of a-Si BIPV/T system. It was found that the overall energy efficiency of the BIPV/T system was nearly 17–20% higher and the exergy efficiency was nearly 1.5–2% higher than those of the similar BIPV system, and the use of BIPV/T system reduced the unit power generation cost by 12–25% than that of the similar BIPV systems [37].

The building integrated photovoltaic–thermal (BIPV/T) system was investigated. Fig. 15 illustrates the schematic diagram for the BIPV/T system. The investigated BIPV/T system consisted of 20 PV modules with a total area of 10 m^2 which was mounted at 30° (latitude of Kerman). Dimensions of the duct under the PV

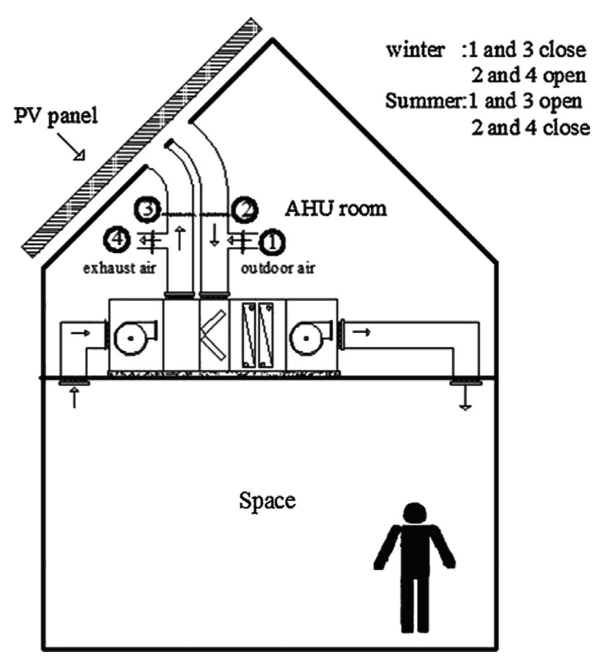

Fig. 15. The schematic diagram for the BIPVT system [38].

modules, as air passage, were 2 m × 0.3 m and a length of 5 m. The results indicated that the exhaust and ventilation airs in heating ventilating air conditioning systems could be used as the cooling fluid of the PV panels and increased their efficiency, and the heat rejection of the PV panels could provide some part of the ventilation air heating load. It was noted that using exhaust air as the cooling fluid for cooling of a PV panel with 10 m^2 surface area, increased electricity production with the amount of 10.1% caused 129.2 kW h extra electrical energy production during a year. It was found that using ventilation air as the cooling fluid for cooling of a PV panel with the 10 m^2 surface area, provided 10.2% of the ventilation air heating load also increased the PV panel electricity production with the amount of 7.2%, and the 3400.4 kW h energy was recovered through the ventilation air heating by solar energy and 55.9 kW h extra electricity was generated by PV panels on a yearly basis [38].

The performances of building integrated semitransparent photovoltaic thermal (BISPV/T) and building integrated opaque photovoltaic thermal (BIOPV/T) systems each integrated to the roof of a room with and without the air duct were evaluated. Comparative analysis was performed between BISPV/T and BIOPV/T systems each integrated to the facade and roof of a room with and without the air duct for the cold climatic conditions of Srinagar, India. It was found that the maximum room air temperature rise was 18 °C for a semitransparent photovoltaic thermal (SPV/T) roof without the air duct and the minimum room air temperature rise was 2.3 °C for the opaque photovoltaic thermal (OPV/T) facade with the air duct. The results showed that the room air temperature difference in SPV/T facade and OPV/T facade, and SPV/T roof and OPV/T roof with the air duct was 1.46 °C and 1.13 °C, respectively. It was observed that the room air temperature difference in SPV/T facade and OPV/T facade, and SPV/T roof and OPV/T roof without the air duct was 9.80 °C and 9.55 °C, respectively. The results also indicated the maximum room temperature achieved was 22.0 °C in SPV/T roof without the air duct for an ambient temperature of 4.4 °C. It was also noted that the room air temperature increased from 9.4 to 15.2 °C for SPV/T roof for a given climatic and design parameters as air mass flow rate through duct increased from 0.85 to 10 kg/s [39].

The effects of the packing factor on the performances of a building integrated semitransparent photovoltaic thermal (BISPV/T) system with the air duct were carried out. Energy and exergy investigations were performed by considering different packing factors (0.42, 0.62, and 0.83) of the PV module namely monocrystalline silicon (m-Si), polycrystalline silicon (p-Si), amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and a heterojunction with thin layer (HIT). The results indicated that the decrease in the packing factor from 0.83 to 0.42 decreased the module temperature by 10.0 °C thereby increasing the module efficiency by 0.2–0.6% and room temperature by 3.0 °C. It was seen that the maximum annual electrical energy for HIT was 813 kW h and 788 kW h for 0.62 and 0.83 respectively, and the maximum annual thermal energy for a-Si was 79 kW h and 61 kW h for 0.62 and 0.83 respectively. The results also showed that the maximum overall annual thermal energy and exergy in HIT was 2212 kW h and 831 kW h for the packing factor of 0.62 and 2129 kW h and 799 kW h for the packing factor of 0.83. It was concluded that the annual thermal energy and exergy in HIT for 0.62 the packing factor was 83 kW h and 32 kW h higher than 0.83 packing factor of the PV module [40].

The evaluation of both the electrical power generating ability and the solar heat collection capacity during winter of six variations of the experimental thermal-PV hybrid wallboard was presented. Fig. 16 illustrates the schematic diagram of a thermal-PV hybrid wallboard. Solar heat was collected in the form of heated air circulating in the air gap between the hybrid wallboard and the thermal insulation of the exterior walls. The results showed that the average conversion efficiency based on the solar radiation at an inclination angle of 80° and the total cell area was 11.2% and 11.4% for wallboards PV3 and PV5, respectively: polycrystalline silicon modules and no glass plate covering the wallboard. It was noted that the average conversion efficiency for the amorphous silicon cells of PV1 (without a glass cover) was 3.6%.

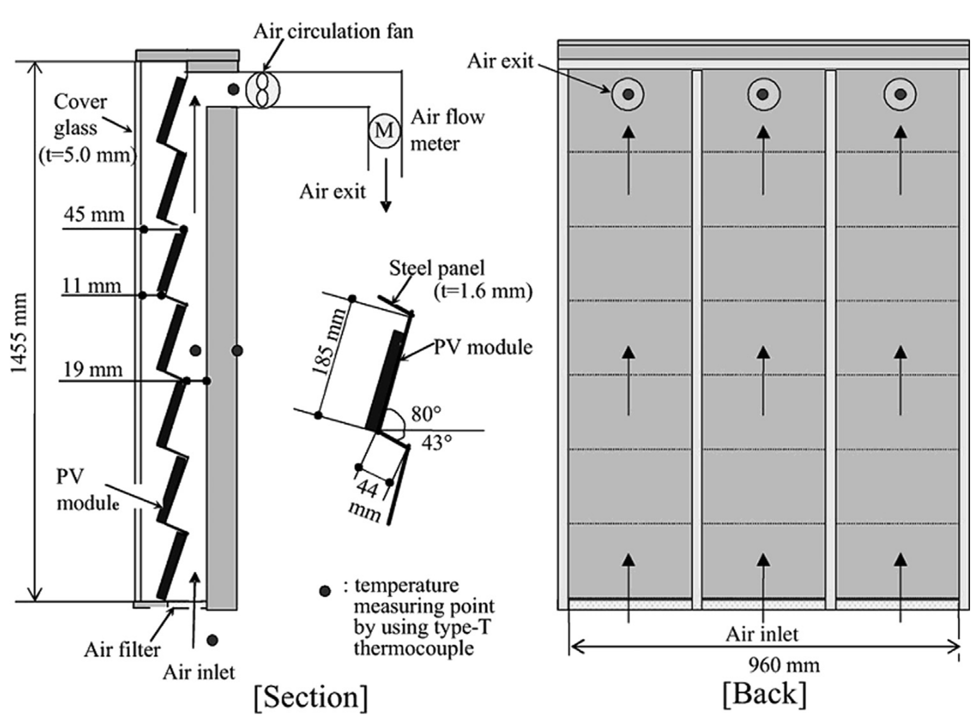

Fig. 16. The schematic diagram of a thermal-PV hybrid wallboard [41].

It was also concluded that the average thermal collector efficiency based on the perpendicular projected wall area and vertical global solar radiation changed from 20.2% to 22.3% for wallboards without glass covers and from 29.2% to 36.9% for those with glass covers [41].

4. Concentrating photovoltaic–thermal systems

The performances of a parabolic trough photovoltaic/thermal collector with a geometric concentration ratio of 37× were investigated. The measured results indicated that the thermal efficiency was around 58% and the electrical efficiency was around 11%, therefore a combined efficiency was 69% under typical operating conditions. The relationship between temperature and efficiency was measured experimentally for a range of Australian National University (ANU) concentrator cells. It was found that the drop in efficiency with temperature was in the order of 0.35%/°C relative, influenced primarily by a drop in open circuit voltage [42].

The performances of low concentrating photovoltaic/thermal systems were evaluated. The measured results showed that the electrical efficiency was 6.4% at 25 °C water outlet temperature while the electric efficiency temperature dependence was 0.3%/°C. It was found that the measured total peak power was 61 W/m^2 of the total glazed area at 28 °C inlet and 39 °C outlet water temperature and 997 W/m^2 incident beam radiation. The results presented that the hybrid beam optical efficiency and the heat loss coefficient were 0.45 and 1.9 W/°Cm^2 of the total glazed area. It was noted that the measured thermal peak power was 435 W/m^2 of total glazed area at the same conditions [43].

The energy and exergy analysis of a novel concentrating photovoltaic combined system (CPVCS) based on the spectral decomposing approach was carried out. Fig. 17 shows the schematic diagram of the concentrating photovoltaic combined system. The proposed CPVCS with a hot mirror placed in the focal region could transfer solar energy spectrum behind the visible region, and reflect the infrared (IR) and ultraviolet (UV) parts. The IR and UV rays were reflected by appropriate optical design and were sent to vacuum tube, where could be evaluated as heat energy. The results indicated that the electrical power produced per solar cells in CPVCS was 4.6 W and thermal power produced in vacuum tubes was 141.21 W. It was found that the energy efficiencies of a concentrator, vacuum tube and overall CPVCS were 15.35%, 49.86% and 7.3% respectively, and the exergy efficiencies of the concentrator, vacuum tube and overall CPVCS were

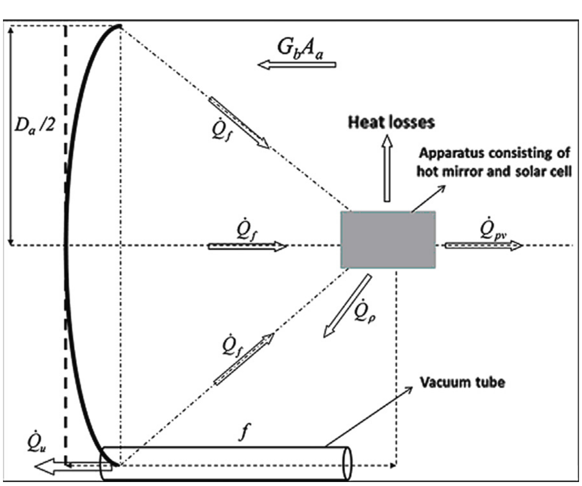

Fig. 17. The schematic diagram of the concentrating photovoltaic combined system [44].

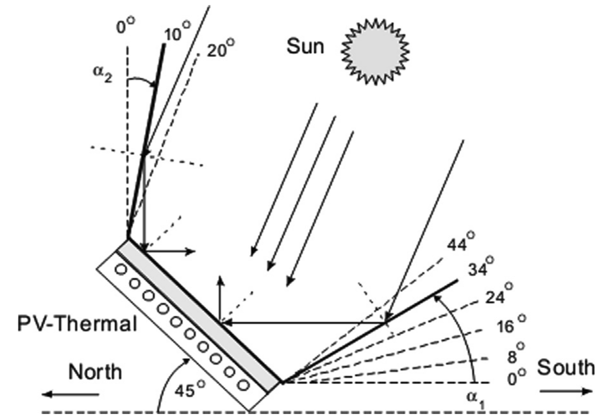

Fig. 18. The schematic diagram of the PV/thermal collector with solar radiation concentrators [45].

12.06%, 2.0% and 1.16% respectively. The results also showed that exergetic improvement potential of concentrating dish, the vacuum tube and solar cells were 426.66 W, 254.26 W and 21.77 W respectively [44].

The influences of reflectance from flat plate solar radiation concentrators made of Al sheet and Al foil on energy efficiency of PV/thermal collector were investigated. Fig. 18. presents the schematic diagram of the PV/thermal collector with solar radiation concentrators. The PV/thermal collector with dimensions 1.37 m × 0.72 m and the surface 0.986 m^2 consisted of electrolitically colored anodized aluminum box, thermal insulation from mineral wool, PV/thermal absorber, Al sheet on the back and protective glass on the front side. The PV/thermal absorber was composed of interconnected Al sheets with copper tubes installed at the bottom and solar module with solar cells made of monocrystal silicon which was fixed to Al sheets. The concentrators with dimensions of 1.37 m × 0.72 m were made of Al sheet and Al foil. The results showed that total daily thermal energy generated by the PV/thermal collector with concentrators made of Al sheet in optimal position was by 39% higher than the total generated thermal energy obtained by the PV/thermal collector without the concentrator, and the total daily thermal energy generated by the PV/thermal collector with concentrators made of Al foil in optimal position was by 55% higher than the total generated thermal energy obtained by the PV/thermal collector without the concentrator. It was found that the total daily electrical energy generated by the PV/thermal collector with concentrators made of Al sheet in optimal position was by 8.6% higher than the total generated thermal energy obtained by the PV/thermal collector without the concentrator, and the total daily electrical energy generated by PV/thermal collector with concentrators made of Al foil in optimal position was by 17.1% higher than the total generated thermal energy obtained by the PV/thermal collector without the concentrator [45].

The performances of the 10 m^2 trough concentrating photovoltaic/thermal (TCPV/T) system with an energy flux ratio of 20 using the GaAs cell array and a concentrating silicon cell array were investigated. The area of the reflecting mirror was 1.97 × 5.08 m^2, and the effective aperture area of the parabolic mirror was 9.25 m^2. The mirror reflectivity was 0.69 with 20 times energy flux concentration ratio which had 31 times geometric concentration ratio. The focal line width of the concentrating light was 0.06 m. The experimental results indicated that under 20× concentrating irradiance, the efficiency of the GaAs cell array was 23.83%, and that of the concentrating silicon cell array was 13.89%. It was observed that the electrical efficiency and thermal efficiencies of the TCPV/T system with the concentrating silicon cell array

were 7.51% and 42.41% respectively, and those with the GaAs solar cell array were 9.88% and 49.84% respectively [46].

The application for the concentrating photovoltaic/thermal (CPV/T) collector was investigated. The hybrid collector, which generated electricity and hot water simultaneously, was used to drive a hybrid air conditioner that separated the sensible and latent loads. The hybrid air conditioner consisted of a solid desiccant wheel cycle (DWC) and a conventional vapor compression cycle (VCC). The DWC was driven by the collector thermal output and the VCC was driven by the electrical output. The results indicated that as the water mass flow rate through the collector array increased, the thermal output decreased and the electrical output increased until both reached a nearly constant value, and also showed that as the water mass flow rate increased, the increase in the water temperature across the collector decreased, which led to lower PV cells temperature and the higher the electricity efficiency. The simulation results presented that the coefficient of performance (COP) of the hybrid solar air conditioner was higher than that of a VCC powered by PV panels and a solar absorption cycle. The cooling COP was 0.68, 0.34 and 0.29, respectively [47].

The system simulation of a 6.2 kWp linear concentrating photovoltaic system (LCPV) with an active cooling system was performed. The results indicated that the LCPV system could generate 5089 kW h of thermal energy and 14,215 kW h of electricity with a multijunction cell efficiency average of 34.75%. It was found that this resulted in a significant reduction of totaling $1623 and $202 in purchasing electricity and natural gas throughout the year, respectively [48].

The performances of a novel low-concentrating solar photovoltaic/thermal integrated heat pump system (LCPV/T-HP) with both electricity and heat outputs were carried out. The solar photovoltaic/thermal collector with fixed truncated parabolic concentrators reflecting the incident sunlight onto the surface of PV cells was also used as the evaporator of the heat pump system. The experimental results indicated that the LCPV/T-HP system could obtain an averaged COP of 4.8 for heating water from 30 °C to 70 °C on a sunny summer day, with an output electrical efficiency of 17.5%, which was 1.36 times higher than that of the LCPV system. The analyzed results also suggested that flux concentrating rate of the fixed parabolic concentrators was 1.6 [49].

The performance analysis of water cooled concentrated photovoltaic (CPV) system was performed. The experimental results indicated that the operating temperature of the CPV module under water cooling was reduced under 60 °C and therefore the efficiency of the CPV was increased. It was noted that the output electricity of the concentration solar cell was 4.7–5.2 times higher than the fixed cell. The results also showed that the maximum produced electricity at solar noon from the concentration solar cell was 71.13 W, and from the fixed cell was 16.55 W [50].

5. Photovoltaic–thermal heat pump systems

The photovoltaic and thermal performances of a photovoltaic solar assisted heat pump (PV-SAHP) system were investigated. The experiments of four different operating modes with condenser outlet water temperature at 20 °C, 30 °C, 40 °C and 50 °C were performed in a 4-day period under the solar radiation, ambient temperature and wind velocity was 606 W/m^2, 13.7 °C and 3.2 m/s respectively. The results showed that the max COP (coefficient of performance), max $COP_{p/t}$, average COP, average $COP_{p/t}$ and average photovoltaic efficiency were 10.4, 16.1, 5.4, 8.3, and 13.4% respectively. These indicated that the thermal performances of the PV-SAHP system were better than the conventional heat pump systems and at the same time, the photovoltaic efficiency was also higher [51].

The experimental investigation on operation performances of a photovoltaic–thermal solar heat pump air-conditioning system was performed. The schematic diagram of the experimental system on the photovoltaic–thermal solar heat pump air-conditioning system is shown in Fig. 19. The PV/T evaporator was composed of photovoltaic module, aluminum plate, copper tubes and heat insulation materials. The dimension of PV/T evaporator was a length of 1500 mm, a width of 750 mm and a thickness of 100 mm. The PV/T evaporator was insulated with polyurethane of

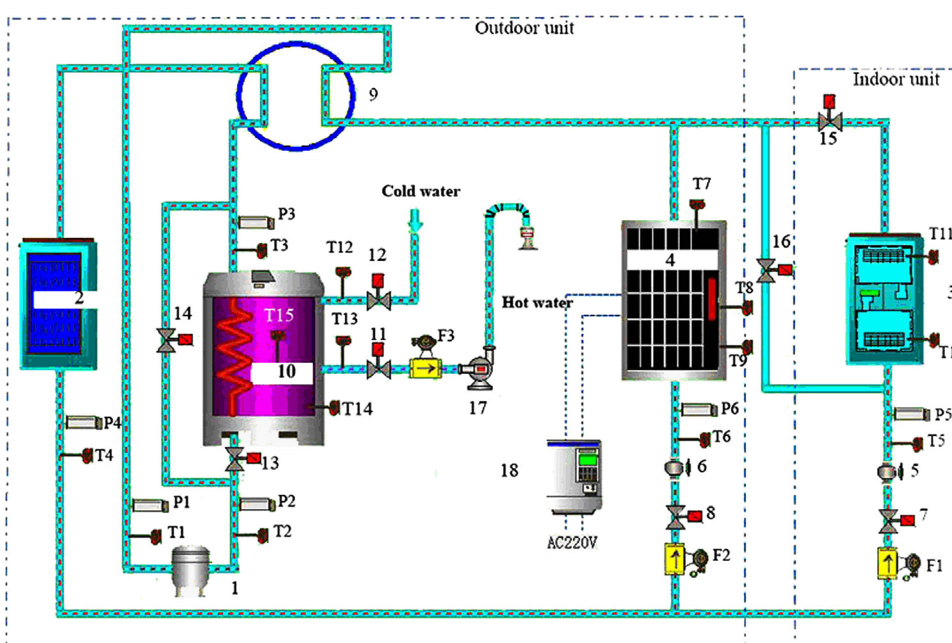

Fig. 19. The schematic diagram of the experimental system: (1) compressor, (2) heat exchanger in outdoor unit, (3) heat exchanger in indoor unit, (4) PV/T evaporator, (5 and 6) throttle valve, (7 and 8) electromagnetic valve, (9) four-way electromagnetic valve, (10) water heater, (11–16) electromagnetic valve, (17) circulating pump and (18) DC–AC convertor [52].

50 mm thickness to minimize the heat transfer to surroundings. The dimension of photovoltaic module was a length of 1482 mm, a width of 676 mm and a thickness of 35 mm. The open circuit voltage and optimum operating voltage were respectively 22 and 17.4 V, the short circuit current and the optimum operating current were respectively 8.09 and 7.47 A, and the maximum power was 130 W. The experimental results indicated that during the whole operation period, the photovoltaic–thermal solar heat pump air-conditioning system could stably work, and the evaporation pressure was stable at 0.36 MPa and the condensation pressure was stable between 0.97 MPa and 1.15 MPa. It was found that the COP of the system was between 2.75 and 2.85, and the temperature of the PV module in the PV/T evaporator decreased from 52 °C to 8 °C and the temperature of conventional the PV module increases from 52 °C to 62 °C. The results also showed that the photovoltaic efficiencies of the PV module in the PV/T evaporator increased from 9.4% to 10.9%, the photovoltaic efficiencies of conventional PV module decreased from 8.7% to 8.0%. It was observed that the mean photovoltaic efficiency of the PV module in the PV/T evaporator could reach 10.4%, and could improve 23.8% in comparison with that of the conventional PV module. It was known that the water temperature in the water heater could rise from 20 °C to 42 °C, and the receiving heat capacity of the water heater could increase to 9400 kJ. The experimental results indicated that the photovoltaic–thermal solar heat pump air-conditioning system had better performances [52].

The numerical study on the direct expansion heat pump system incorporating a photovoltaic/thermal (PV/T) solar collector acting as the evaporator was carried out to evaluate the energy performance of the heat pump and the electrical and thermal performances of the PV cells. The simulation results indicated that the monthly average thermal efficiency varies from 0.711 to 0.794 with an average of 0.752 and the monthly average electrical efficiency varies from 0.148 to 0.162 with an average of 0.155. It was found that the COP of the PV/T heat pump system varied from 4.65 to 6.16 with an average of 5.35, and the condenser thermal capacity ranging from 33 to 174 W would provide the heat source for space heating and domestic hot water [53].

The novel PV/e roof module was proposed to act as the roof element, electricity generator and the evaporator of a heat pump system. A theoretical model was developed to optimize the system structure and simulate its performances. The results indicated that the combined system would operate at 10 °C of evaporation temperature and 60 °C of condensation temperature. It was found that under a typical Nottingham (UK) operating condition, the modules would achieve 55% of thermal efficiency and 19% of electrical efficiency, while the module-based heat pump system would have an overall efficiency of above 70%. These showed that the PV/e roof modules-based heat pump system could achieve significant improvement in thermal and electrical efficiencies [54].

The performance analysis of the photovoltaic solar assisted heat pump (PV-SAHP) system was performed based on the distributed parameters' approach. The experimental rig was also built to verify the real performance of the system as compared to the simulation model prediction. The results indicated that the PV-SAHP system had superior thermal performance with 8.4 of maximum COP and 6.5 of average COP during the test period under 30 °C of the hot water temperature, 603 W/m^2 of the averaged solar radiation intensity and 15.8 °C of the averaged ambient temperature. It was noted that the maximum condenser capacity was about 2400 W, and the average value was 2120 W. It was also found that the average photovoltaic efficiency was 13.7%, and the average photovoltaic power was 423 W, which was more than 313 W of the average compressor consumed power [55].

The novel solar photovoltaic/loop-heat-pipe (PV/LHP) heat pump system for hot water generation was proposed. The experimental rig was set up and utilized to acquire the relevant measurement data as compared to the simulation model prediction. The results showed that under the given experimental conditions, the electrical, thermal and overall efficiency of the PV/LHP module were around 10%, 40% and 50% respectively whilst the coefficient of performance (COP) of the PV/LHP system was 8.7. It was found that the lower solar radiation, lower air temperature, higher air velocity and smaller cover number resulted in enhanced electrical efficiency but reduced thermal efficiency of the module, and the lower heat-pump's evaporation temperature and larger number of heat absorbing pipes resulted in rise to both thermal and electrical efficiencies of the module [56].

The performances of a photovoltaic solar assisted heat pump (PV-SAHP) with variable-frequency compressor were investigated. The mathematical models were proposed to evaluate the energy performance of the combined system based on the weather conditions of Tibet. The simulation results indicated that the COP varied from 4.57 to 7.25 with an average of 6.01, and the maximum condenser thermal capacity was 3170 W with the average value being 2200 W. It was found that the photovoltaic output power varied from 152.6 W to 662.3 W, the total power generated was up to 4.7 kW h, and the compressor consumed power changed within 139.1–438.4 W with an accumulation of 3.6 kW h in one day. The results also showed that the daily averaged electrical efficiency, thermal efficiency and overall efficiency were 0.135, 0.479 and 0.625 respectively in this specific application [57].

The photovoltaic-integrated solar heat pump (PV-SAHP) system was proposed as a sustainable alternative. Numerical analysis was performed by using a dynamic simulation model and the Typical Meteorological Year (TMY) weather data of Hong Kong. The results showed that the system could achieve a yearly average COP of 5.93 and electricity efficiency of 12.1%, the overall energy output was therefore considerably higher than the conventional heat pump plus PV "side-by-side" system. It was found that within a year, the PV-SAHP system would have better performance in summer time from May to October, when the monthly average COP could reach six or higher. The results also indicated that in July as compared to January, the monthly average values of COP were 6.89 and 5.05 respectively, and the amount of hot water produced in summer could be more than double of that in winter [58].

The experimental investigation on a hybrid photovoltaic/heat pump system was performed. Fig. 20 illustrates the schematic diagram of a hybrid PV panel-based heat pump system. Three testing modes were proposed to investigate the effect of solar radiation, condenser water flow rate and condenser water supply temperature on energy performance. The results showed that the COP varied from 2.9 to 4.6, responding to the radiation from 200 W/m^2 to 800 W/m^2, at the constant condenser water flow rate of 2 L/min and water supply temperature of 35 °C. It was found that the electrical efficiency of PV panel in the heat pump system was improved by up to 1.9% as compared with that without cooling. It was also observed that the COP reduced from 5.2 to 3.2, responding to the condenser supply temperature from 25 °C to 45 °C, at the radiation of about 600 W/m^2 and the condenser water flow rate of 2 L/min. The result also indicated that the COP decreased from 6.7 to 2.8, responding to the condenser water flow rate from 1 L/min to 5 L/min, at the radiation of about 600 W/m^2 and the condenser water supply temperature of 35 °C [59].

The experimental investigation of the photovoltaic solar-assisted heat-pump/heat-pipe (PV-SAHP/HP) system was carried out. A series of experiments were conducted in Hong Kong to study the performance of the system when operating in the heat-pipe and the solar-assisted heat-pump modes. The results indicated that the PV-SAHP/HP system could reach a daily average energy efficiency of 61.1–82.1% and an exergy efficiency of 8.3–9.1% when operating in the solar-assisted heat-pump mode. It was

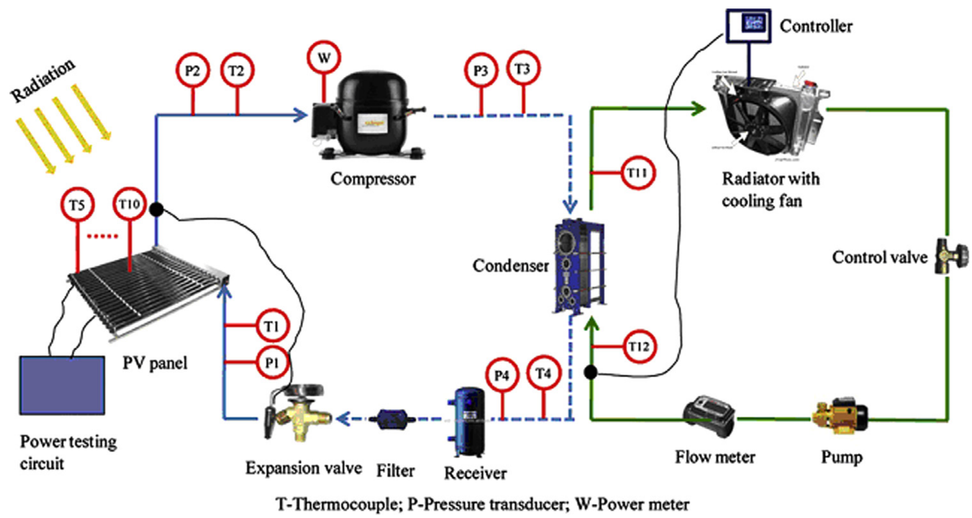

Fig. 20. The schematic diagram of a hybrid PV panel-based heat pump system [59].

noted that the daily average heat-pump COP could reach 4.01 as the solar radiation was strong, and the daily average system energy and exergy efficiencies were approximately 36.5–38.4% and 7.4–7.8% respectively, when the PV-SAHP/HP system operated in the heat-pipe mode under strong solar radiation [60].

The model of dynamic characteristics in a hybrid PV/T heat pump system was established. The results showed that the solar radiation intensity and the evaporation temperature in the PV/T heat pump system had an influence on the solar panel temperature, the solar photovoltaic efficiency, the solar photovoltaic power, and the heat transfer rate of the solar panel in a hybrid PV/T heat pump system. It was found that the solar photovoltaic efficiency was 11.2%, 11.1%, and 11%, the solar photovoltaic power was 92.2, 91.7, and 91.3 W, the heat transfer rate of a solar panel was 416, 410, and 405 W, and the coefficient of performance of the PV/T heat pump system was 6.0, 6.9, and 7.9 when the evaporation temperatures in the PV/T evaporator were 5 °C, 10 °C, and 15 °C respectively [61].

The simulation of a photovoltaic/thermal heat pump (PV/T-HP) system with a modified collector/evaporator (C/E) was performed. The results showed that the PV/T-HP system with the modified C/E could achieve a higher COP by 7%, a higher thermal efficiency by 6% and a relative electrical efficiency coefficient by 2% as compared to those of the PV/T-HP system with a conventional C/E. The simulation results also indicated that the PV/T-HP system with the modified C/E could efficiently generate electricity and heating 150 L water up to 50 °C in both Nanjing and Hong Kong, China [62].

6. Case studies

Some case studies of PV/T water based collectors with polycrystalline silicon cell, amorphous silicon cell and monocrystalline silicon cell were summarized in hot and humid climate of Malaysia. The results presented that the thermal efficiency and electrical efficiency of the PV/T water based collectors with polycrystalline silicon cell are 50.12% and 11.98%, and the thermal efficiency and electrical efficiency of the PV/T water based collectors with amorphous silicon cell are 72% and 5% [63].

The detailed studies of a new design of absorber collector under the meteorological conditions of Malaysia were carried out. The parameters like thermal conductivity and fin efficiency, type of cells, type of coolant and operating conditions were analyzed. The performances of the water-based PVT collector for building-integrated applications were evaluated. The results indicated that the electrical, thermal and combined photovoltaic thermal efficiencies for the amorphous silicon (a-Si) PV/T were 4.9%, 72% and 77%, and the electrical, thermal and combined photovoltaic thermal efficiencies of the crystalline silicon (c-Si) PV/T were 11.6%, 51% and 63% when the flow rate was 0.02 kg/s, the solar radiation level was between 700 W/m^2 and 900 W/m^2 and the ambient temperature was between 22 °C and 32 °C [64].

The electrical and thermal performances of a single pass hybrid photovoltaic/thermal (PV/T) air collector were investigated for two selected case studies in Iraq. The parameters of the PV/T collector such as cell and air temperatures, thermal gain, PV current and voltage, and fill factor were analyzed. The influences of most important operating conditions like sky, inlet and cell temperatures, air flow rate and incident solar radiation on the performance of the hybrid collector were identified. In order to acquire the performances of a single pass hybrid PV/T air collector for two case studies, the improved mathematical thermo-electrical model was applied for a winter day (22 January 2011) in Baghdad city and for a summer day (20 May 2011) in Fallujah city. The results showed that the electrical, thermal and overall collector efficiencies were 12.3%, 19.4% and 53.6% for the winter day, and the electrical, thermal and overall collector efficiencies were 9%, 22.8% and 47.8% for the summer day [65].

The hybrid photovoltaic/thermal (PV/T) systems consisting of polycrystalline silicon and amorphous silicon PV modules combined with water heat extraction units were investigated by TRNSYS program. The performances of the industrial process heat system operated at two load supply temperature 60 °C and 80 °C were analyzed. The system consists of hybrid PV/T collectors with 300 m^2 and a 10 m^3 water storage tank. The results indicated that the electrical production of the system employing polycrystalline solar cells was more than the amorphous ones but the solar thermal fraction was slightly lower. A non-hybrid PV system produced about 25% more electrical energy but the present system also covered a large percentage of the thermal energy of the industry [66].

The performances of commercially available PV/T systems for electricity and domestic hot water production were evaluated for use in three European countries such as Athens, Munich and Dundee. The PV part of the hybrid systems installed at three locations can be compared by evaluating their performance indices like yield, performance ratio and conversion efficiency. It was found that the system at Athens displayed the highest annual yield (1390.3 kW h/kWp) in comparison with the other

two systems due to high solar irradiation and small installed power, however, the system at Dundee presented the lowest annual yield (916.1 kW h/kWp), even though it produced more energy per annum in comparison with the other two systems due to the large surface area of photovoltaic panels. The results indicated that the system installed in Athens, which had the low performance ratio (79.8%) and high solar irradiation, produced more energy with respect to the system size in comparison to the installation at Dundee, which had a high performance ratio (85.2%) and low solar irradiation. It was also noted that the conversion efficiency was nearly the same for the three systems due to the PV efficiency is insensitive to the solar irradiance within the practical working range, and the slightly higher conversion efficiency at Dundee is also mainly due to prevailing lower ambient temperatures in comparison with those of two other cities [67].

7. Obstacles and respective solutions

There are a number of formidable obstacles needing to be overcome for the PV/T technology in the way of eliminating the traditional fossil energy including increasing photovoltaic efficiency and service life of cells, modules, inverters, etc. and reducing the total system cost, especially cost of production, materials and maintenance. Manufacturing solar cells from crystalline silicon is the most common approach. Since the 1960s, the field of crystalline silicon solar cells has made significant improvements in thickness thinning, cutting technique, chip size, and photovoltaic efficiency. However, the sustained cost cutting of solar cells slows down gradually under present technical conditions. With the decrease of cell thickness, the mechanical strength of crystalline silicon descends obviously which makes the manufacturing process more difficult. The key to reduce the price of solar systems is the technical progress of solar cells. There are two approaches to achieve this goal, one is to reduce the manufacturing cost by process improvement and structural development of solar cells, and the other one is to increase photovoltaic efficiency by technological innovation of solar cells.

The future development and research will focus on the thin film silicon solar cells. Compared with conventional crystalline silicon solar cells, thin film silicon solar cells have a range of advantages including less material consumption, less manufacture energy consumption and low structural weight. With the development of technology, the manufacturing technique of thin film silicon solar cells will become more and more mature and the cost of solar systems will reduce accordingly in the near future. Predictably, the PVT technology with the huge development potential and broad market prospects will be the most necessary alternative to eliminate the traditional fossil fuel.

Compared with the advanced countries and regions in the world, the solar-powered building integration technology is still in the demonstration and pilot phase in China, and the building-integrated photovoltaic (BIPV) is more common than building-integrated photovoltaic/thermal (BIPV/T). However, under the dual pressure of energy demand and environmental protection, BIPV/T will be one of the most important fields of building energy saving. With the continuous development of solar technology and energy saving mode, the PV/T technology will surely become an important part of the solar-powered building integration systems, and the new type buildings with zero energy consumption will enter the ordinary families.

8. Conclusions

The performance evaluations and applications of the photovoltaic–thermal collectors and systems were summarized. The performances of the photovoltaic–thermal air collectors and photovoltaic–thermal water collectors were described. The applications of the photovoltaic–thermal systems, such as building integrated photovoltaic–thermal systems, concentrating photovoltaic–thermal systems and photovoltaic–thermal heat pump systems were presented. The following conclusions could be drawn:

1. The hybrid photovoltaic/thermal (PV/T) collectors can simultaneously provide electricity and heat, achieving a higher conversion rate of the absorbed solar radiation than standard PV modules. The PV/T collectors can extract heat from PV modules, heating water or air to reduce the operating temperature of the PV modules and improve the electrical efficiency to a high value.
2. The building integrated photovoltaic thermal (BIPV/T) system has the potential to become a major source of renewable energy. The BIPV/T system has been used as the rooftop of a building to generate higher electrical energy per unit area and to produce necessary thermal energy required for space heating.
3. The thermal energy generated by the PV/thermal collector with concentrators is higher than that by the PV/thermal collector without the concentrator. The electrical energy generated by the PV/thermal collector with concentrators is higher than that by the PV/thermal collector without a concentrator.
4. The photovoltaic–thermal heat pump systems have a relatively high thermal performance with an improved photovoltaic efficiency by utilizing thermal energy from PV modules and decreasing the working temperature of the solar cells. This indicates that the photovoltaic–thermal heat pump system has a good application potential.
5. As previously mentioned, the building integrated photovoltaic thermal (BIPV/T) system is efficient, economical, environmental and ecological friendly, but it still has some defects, especially the photovoltaic–thermal component integrated into buildings has high cost and low efficiency, and the system performance is unstable due to the weather effect. With the development of the photovoltaic technology, more efficient and lower cost PV/T collector will be applied to the BIPV/T system.
6. Compared with the photovoltaic–thermal air collectors and photovoltaic–thermal water collectors, the photovoltaic–thermal heat pump systems using a refrigerant as working fluid performs quite well in the photovoltaic–thermal performance. From the analysis above, it can be known that the working temperature of the solar cell drops down to a certain degree and the PV module works in an ideal state. The photovoltaic–thermal heat pump systems can integrate photovoltaic cells and heat pump air-conditioning system. This system can provide cooling in summer, heating in winter and hot water in all year.

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